5-2018

The Effects of Surge Flows on Residential Water Meters

Ryan P. Weller
Utah State University

THE EFFECTS OF SURGE FLOWS ON RESIDENTIAL WATER METERS

by

Ryan P. Weller

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

Approved:

____
Steven L. Barfuss, M.S.
Major Professor

____
Wade H. Goodridge, Ph.D.
Committee Member

____
Michael C. Johnson, Ph.D.
Committee Member

____
Mark R. McLellan, Ph.D.
Vice President for Research and
Dean of the School of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2018

ABSTRACT

The Effects of Surge Flows on Residential Water Meters

by

Ryan P. Weller, Master of Science

Utah State University, 2018

Major Professor: Steven L. Barfuss
Department: Civil and Environmental Engineering

All residential water meters have published flow rates for which they will operate as designed. These specifications include a maximum operating flow rate, which is recommended not to exceed. However, there are situations which may cause a meter to flow above the maximum flow rate. This thesis explores what effect these surge flows have on residential water meters.

Twenty-one 5/8” x 3/4” meters were tested in this study: three oscillating pistons, six nutating disks, nine ultrasonic, and three electromagnetic. Testing was done at the Utah Water Research Laboratory using a gravimetric test bench specifically designed for residential water meter testing.

The results of this study showed that the ultrasonic meters decreased significantly in accuracy above 35 gallons per minute and produced the most pressure loss of the meters in this study. The nutating disk and oscillating piston meters were found to be accurate through nearly all surge flow rates tested. Measured pressure losses were less than the ultrasonic meters but more than the electromagnetic meters. The electromagnetic meters were found to be accurate up to 55 gallons per minute and produced the least amount of pressure loss.

No meters mechanically failed even though flow rates through each meter reached anywhere from 2 to 3.5 times the published maximum operating flow rate. Accuracy tests performed after surge flows showed that some nutating disk and oscillating piston meters decreased in accuracy at flow rates below two gallons per minute. The electronic meters had similar accuracy before and after surge flows.

(45 pages)

PUBLIC ABSTRACT

The Effects of Surge Flows on Residential Water Meters

Ryan P. Weller

All residential water meters have published flow rates for which they will operate as designed. These specifications include a maximum operating flow rate, which is recommended not to exceed. However, there are situations which may cause a meter to flow above the maximum flow rate. This thesis explores what effect these surge flows have on residential water meters.

Twenty-one 5/8” x 3/4” meters were tested in this study: three oscillating pistons, six nutating disks, nine ultrasonic, and three electromagnetic. Testing was done at the Utah Water Research Laboratory using a gravimetric test bench specifically designed for residential water meter testing.

The results of this study showed that the ultrasonic meters decreased significantly in accuracy for tests above 35 gallons per minute. The nutating disk and oscillating piston meters were found to be accurate through nearly all surge flow rates tested. The electromagnetic meters were found to be accurate up to 55 gallons per minute.

Accuracy tests that were performed after surge flows showed that some nutating disk and oscillating piston meters decreased in accuracy at flow rates below two gallons per minute. The electronic meters had similar accuracy before and after surge flows.

ACKNOWLEDGMENTS

I would like to thank my major professor, Steven Barfuss, for the opportunity and guidance he provided throughout this project. I would also like to thank my other committee members, Michael Johnson and Wade Goodridge, for their support throughout the project. My coworkers, Kade Beck and John Chadwick, also spent many hours helping me take this data. I would like to give a special thanks to various people who donated the water meters used in this study. I could not have performed this research without the meters donated by them.

Ryan P. Weller

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Purpose

The residential water meter has reduced the total cost of water utilities by measuring the amount of water used at each connection (AWWA 2012). Each connection has a unique demand pattern that helps determine what meter is best for the connection. Typically, a particular meter is chosen based upon the distribution of flow rates. All residential water meters have published flow rates for which they will operate as designed. These specifications include a maximum operating flow rate. It is recommended that a meter not operate above the maximum flow rate, with the majority of flows in the normal operating range.

However, flow rates above the maximum flow rate do not always determine what meter should be installed at a connection.

> "For example, if 99.9 percent of a customer's flow is below 30 gpm, but the customer has a brief spike once a week of 40 gpm, the meter should be sized to accurately collect the 99.9 percent of the flow, provided the head loss during the spike is acceptable and the meter can survive this surge flow. Most meters can handle brief peak demands and still accurately record low volumes of water, so it is not necessary to ignore 99.9 percent of the volume simply to keep the instantaneous peak demand within the meter's specified flow range" (AWWA 2014).

This statement indicates that meters can be exposed to surge flows as long as the pressure loss is acceptable, meter integrity is not impacted by the surge flow, and surge flows are not a frequent occurrence. Consequently, the purpose of this thesis is to evaluate the impact of surge flows on various residential water meter types in terms of accuracy and pressure loss. This research defines surge flows as flow rates above a meter's maximum operating range.

Objectives

This research had three main objectives. The first objective was to determine how accurate a meter is while experiencing a surge flow. The second objective was to measure the pressure loss of the meter over the operating range and for each of the surge flows. The third objective was to evaluate the accuracy of the meter in the normal operating range after experiencing surge flows to ensure that the high velocities and high pressure losses that occurred during the surge flow did not negatively affect the accuracy of the meter. Accordingly, the accuracy of the meter before and after surge flows were compared to identify what impact surge flows had on the meter.

CHAPTER II

LITERATURE REVIEW

This section reviews previous research conducted about the impact surge flows have on residential water meters and how meter manuals pertain to surge flows. Guidance from meter sizing manuals is discussed, and a few examples of surge flows at a meter connection are presented.

Meter Manuals

The American Water Works Association (AWWA) produces several manuals for residential water meters. The manuals reviewed in this section are for testing (M6) and sizing (M22) residential water meters. This project references the AWWA manuals to quantify meter accuracy limits and discuss meter sizing.

The meters used in this study were 5/8” x 3/4”. The M6 manual (AWWA 2012) produced by AWWA provides accuracy limits for new, rebuilt, and repaired cold-water meters. The manual states that displacement meters (oscillating piston and nutating disk) should read between 98.5%-101.5% of the actual volume at the intermediate and high flow rates of 2 and 15 gpm. These meters have accuracy limits of 95%-101% at the low flow rate of 0.25 gpm. Because AWWA has not published accuracy limits for electronic (ultrasonic and electromagnetic) meters at the time this research was performed, displacement meter accuracy limits were used in this study to quantify the accuracy of the electronic meters.

AWWA also produces the M22 manual (AWWA 2014), which provides guidelines for sizing residential water meters. This manual aids in the selection of water meter size by stating an optimum flow range. As an example, the 5/8” x 3/4” displacement meter flow rates are listed in Table 1 below.

Table 1. AWWA meter standards

Table 6-1 AWWA meter standards

Meter	Minimum Flow Rate, *gpm*	Low-Normal Flow Rate, *gpm*	High-Normal Flow Rate, *gpm*	Maximum Flow Rate *gpm*	Head Loss at Maximum Flow, *psi*
Positive displacement					
5/8 in.	0.25	1	10	20	15

As shown in Table 1, the normal flow rate is between 1-10 gpm. AWWA states that “Excessive flow above the high-normal rate will cause excessive wear” (AWWA 2014). However, the manual further clarifies that a meter can experience periodic demands above the rated capacity. As previously described, AWWA states that “Most meters can handle brief peak demands and still accurately record low volumes of water, so it is not necessary to ignore 99.9% of the volume simply to keep the instantaneous peak demand within the meter’s specified flow range” (AWWA 2014). This literature indicates that a meter can experience flow rates above its rated capacity as long as it is not a frequent occurrence.

Previous Research

Most of the research previously performed on surge flows is from a study done by the Fire Protection Research Foundation (FPRF), a research affiliate of the National Fire Protection Association (Utiskul and Wu 2016). In the study, 16 residential water meters from six manufacturers were tested. The 16 mechanical meters varied in size and type.

All of the meters tested were potable water meters, four being rated for fire flows. The upstream pressure for these tests was held constant at 60 psi. The FPRF study determined that all of the meters were capable of handling high flow rates of approximately 25% to 200% higher than the meter ratings. Some meter registers had abnormal movements while testing high flow rates. They also found that all meters performed within accuracy specifications up to 150% above the meters' normal operating range. Post-test visual inspections on the meters revealed no permanent or physical damage to the water meter components. Overall, their testing showed that the water meters were capable of handling the flow rates expected from fire sprinklers without damage.

The research conducted in this thesis is designed to add to the findings in the FPRF report. Multiple meters of the same manufacturer, type, and size were tested for repeatability. Both electronic and mechanical meters were tested in this study. The effect surge flows had on the meters tested was determined by performing tests in the meters' operating range and comparing the results from before and after surge flows, not by visual inspection.

Surge Flows

This section discusses probable scenarios that may cause a meter to operate at surge flows in a municipal water system. For example, an undersized meter would cause the meter to operate at flow rates above its rated capacity. A burst pipe downstream of the meter may also produce surge flows.

Another source of surge flows can be fire sprinkler demands. The residential application of fire sprinklers is currently required in new one- and two-family dwellings and townhome construction in California, Maryland, and Washington D.C. (NFPA 2018).

The FPRF report (Utiskul and Wu 2016) shows that the amount of water used to fight home fires without fire sprinklers can be 1200% larger than homes with fire sprinklers. Research also shows that the civilian death rate for home fires is 81% lower when a fire sprinkler system is installed (Ahrens 2017). Because of these statistics, it is likely that more states will adopt similar residential fire sprinkler requirements. Currently, the code for fire sprinklers in one- and two-family dwellings (NFPA 13D) does not require the installation of a fire flow meter (NFPA 2016). In addition, the water for fire sprinklers can be supplied by the same connection that supplies potable drinking water. This means all of the flow passes through the same meter. Research done in the FPRF report shows that the average flows for one- and two-sprinkler demands are 28 and 39 gpm, respectively (Utiskul and Wu 2016). Both of these demands are above the maximum rated capacity for the 5/8" x 3/4" meters in this study. Accordingly, surge flows through the meter are likely in the event of a fire sprinkler activating. The use of a residential meter in this application is likely going to increase due to more states adopting fire sprinkler requirements.

CHAPTER III

TEST SETUP AND PROCEDURE

All tests in this study were performed at the Utah Water Research Laboratory using potable drinking water. The meters tested in this study included seven sets of three meters. Three meters of each type were tested to ensure results were repeatable. Twenty-one 5/8” x 3/4” meters from five different manufacturers were tested: three positive displacement pistons (OP), six positive displacement nutating disks (ND), nine ultrasonic (US), and three electromagnetic (EM). Table 2 summarizes the meters tested and lists the meter ID used throughout this paper. All meters tested were 5/8” x 3/4” because this is the most common meter size for single family homes.

Table 2. Summary of meters tested

Meter Manufacturer and Type	Meter ID
Manufacturer A Electromagnetic	MFR A EM
Manufacturer A Oscillating Piston	MFR A OP
Manufacturer B Nutating Disk	MFR B ND
Manufacturer B Ultrasonic	MFR B US
Manufacturer C Nutating Disk	MFR C ND
Manufacturer D Ultrasonic	MFR D US
Manufacturer E Ultrasonic	MFR E US

Each type of meter measures volumes differently. Oscillating piston and nutating disk meters measure volumes by displacing water in a measuring chamber. The disk nutates or the piston oscillates each time water enters and exits the measuring chamber, displacing a known volume of water. These mechanical meters are known as displacement meters. Ultrasonic meters measure water by sending two consecutive high frequency sound signals between two transmitters. The consecutive transmissions travel in the direction of the flow of water and against the flow of water. The meter electronics calculate the difference between the travel times and compute a volume of water. Electromagnetic meters produce a magnetic field to measure water using Faraday's law of induction. The water passing through the magnetic field creates a voltage, which is processed by the onboard electronics into a volume.

All meter registers in this research were electronic. Most meter registers reported volume to the nearest 0.01 gallon. This corresponds to a meter register uncertainty of 0.1%. However, the three ultrasonic meters from manufacturer E reported volume to the nearest 0.1 gallon. This is a meter register uncertainty of 1.0%. All meters used in this study were new off-the-shelf meters.

All laboratory tests used a gravimetric test bench for residential water meters. Two scales were used for weighing the water collected. The scales are traceable to National Institute of Standards and Technology. A scale reading to the nearest 0.05 pounds was used for flow rates 2 gpm and lower. A scale reading to the nearest 0.5 pounds was used for flow rates above 2 gpm. The weight of water collected was always sufficient to ensure weight tank uncertainties at or below 0.06%. This involved collecting a minimum of 10 gallons of water for the small scale and 100 gallons for the large scale. A thermometer reading to the nearest 0.1 ˚F was used to calculate the specific gravity of the water. The weight of water and specific gravity were used to determine the volume of water collected during the test. A stopwatch was used to time each test to determine the flow rate. Flow rates were set using a downstream valve.

The total uncertainty of the test setup was determined following the process outlined in "Analysis of Meter Registry Uncertainty" by Sumrak et al. (2016). This method takes into account all of the random and systematic errors of the test setup and gives a 95% confidence interval for the results. The three meters with a resolution of 0.1 gallons had a maximum test uncertainty of ±1.4%. The rest of the meters in this study had a maximum test uncertainty of ±0.3%.

The following procedural steps were taken during this study:

1. Perform baseline meter accuracy tests at AWWA minimum, intermediate, and maximum flow rates as well as other ultra-low flow rates to understand the accuracy characteristics of the meter prior to operating the meter in surge flow conditions. Develop a pressure loss curve for the meter over the same range of flows.
2. Establish how the meter performs at extremely high flow rates (surge flows). Pressure loss was also determined for these surge flows. The highest surge flow rate tested was determined when one of the three criteria were met:
    a) Lab system capacity was reached
    b) Mechanical failure of the meter occurred
    c) Meter accuracy drastically decreased
3. After surge flows were tested, repeat the baseline accuracy tests in Step 1 to evaluate the impact of surge flows on meter accuracy.

The baseline accuracy tests performed in Steps 1 and 3 included eight different flow rates: 0.0625, 0.125, 0.25, 0.5, 2, 8, 15, and 20 gpm. These flow rates were chosen to determine meter accuracy over a wide range of flows. The same flow rates were tested again for Step 3 to identify if the meters were impacted by surge flows. During surge flow testing, a meter accuracy test at two gpm was occasionally performed to ensure no damage had occurred to the meter. Generally, this two gpm test was performed after the 35 and 50 gpm flow rates. The two gpm test was also performed after any of the three stopping criteria were met (Step 2 above). This procedure was established to help identify if a meter became compromised during testing.

Tests for Steps 1 and 3 were performed with the meters in series on a pressurized supply line from Logan City (Figure 1). The upstream pressure from the supply line

Figure 1. Test setup for the supply line from Logan City

ranged from 80-85 psi. After performing the baseline accuracy tests in Step 1, meters were tested individually for pressure loss at 0.5, 8, 15, and 20 gpm. Pressure loss tests were conducted using a differential pressure gage. The upstream and downstream pressures were measured at five and eight diameters, respectively, using two piezometers in a manifold configuration. The pressure taps were installed at each location 180 degrees apart from each other in the horizontal plane. The upstream pressure was monitored using a pressure gage. The downstream pressure was calculated using the upstream pressure and the differential pressure. The downstream pressure was monitored to ensure there was adequate back pressure provided to avoid cavitation on the downstream side of the meter.

Pressure loss helps indicate whether a meter will be able to meet the demands of a connection. Pressure loss in this study is also an important metric for determining if a meter has mechanically failed. If the meter mechanically fails, blockage may occur and cause a significant increase in pressure loss.

Surge flow tests (Step 2) were performed using a pressurized culinary water line from Logan City until flow capacity was reached. When flow capacity was reached, higher flow rates were obtained by running off of two pumps connected in series. The pumps provided up to 140 psi. It should be noted that the author recognized the flow rates obtained using the two pumps are quite high and are not expected to be practical in a normal distribution system. However, this research was performed to see how the meters would perform at flow rates well above the high-normal operating range as well as to determine if the meter remains accurate after being subjected to excessively high flow rates. The pumps were fed from a reservoir filled with potable drinking water from Logan City. Figure 2 is a picture of the test setup with pumps in series. The first meter of each set of three was tested by increasing the flow in 5 gpm increments from 20 gpm up to the stopping criteria. The other two meters in the set increased in 5 gpm increments until 45 gpm, after which they increased in 10 gpm increments. Once the first meter reached any of the stopping criteria, the other two meters were tested at the same flow rates around the stopping criteria to ensure all three meters responded the same.

Figure 2. Test setup for two pumps in series

Step 3 tests were important to identify if a meter was impacted by surge flows. The FPRF research only visually checked meters to see if they had become compromised due to surge flows. Comparing meter accuracy before and after surge flows may be a better metric for determining what impact surge flows have on a meter.

CHAPTER IV

RESULTS

The results of this study are divided into accuracy and pressure loss data. Accuracy data covers the registry of the meter before, during, and after surge flows. Pressure loss data is reported for the normal operating range and surge flows.

Accuracy Data

Every data point in this section represents an average of the three meters tested. The horizontal axis is flow rate in gpm. The vertical axis is registry in percent. Accuracy data for the meters before surge testing is summarized in Figure 3. All meters passed AWWA accuracy limits before surge testing. As expected, meter accuracy generally decreased at flow rates below the AWWA low flow rate for most mechanical meters.

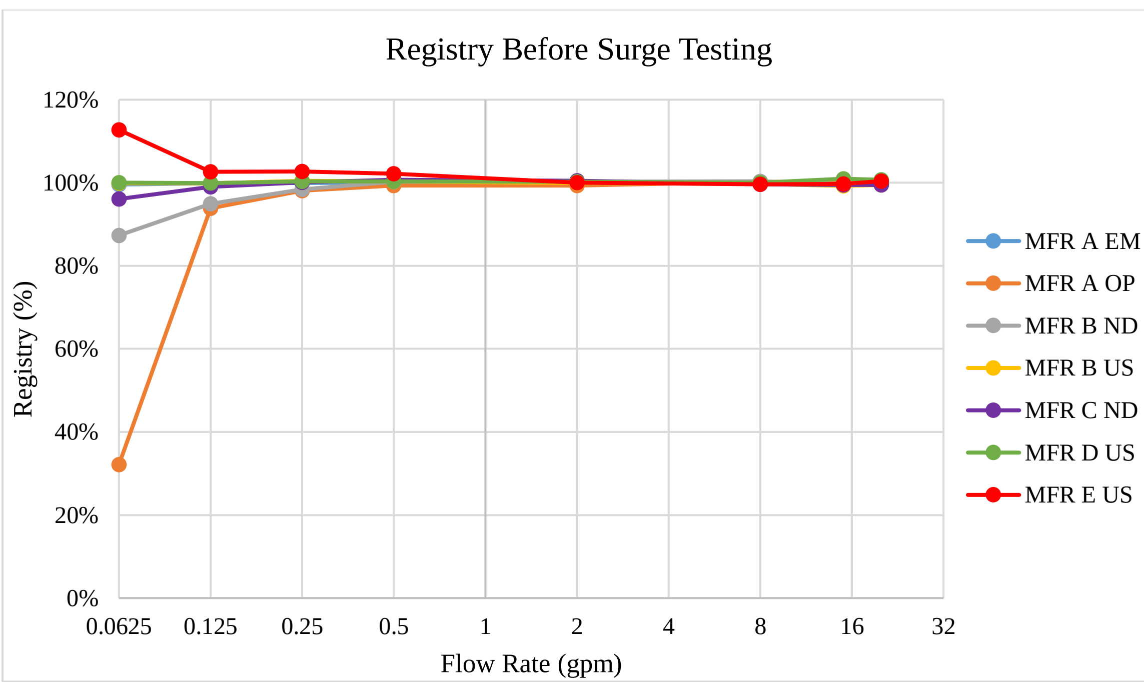

Figure 3. Registry before surge testing

Meter accuracy during surge flows is shown in Figure 4. Interestingly, the mechanical meters in this study were able to reach lab capacity without a significant decrease in accuracy. Manufacturer B nutating disk decreased in accuracy at the highest flows. All electronic meters experienced a significant decrease in accuracy. The ultrasonic meters from all three manufacturers reported under 10% of the volume at 40 gpm. The electromagnetic meter accuracy was under 10% at 60 gpm.

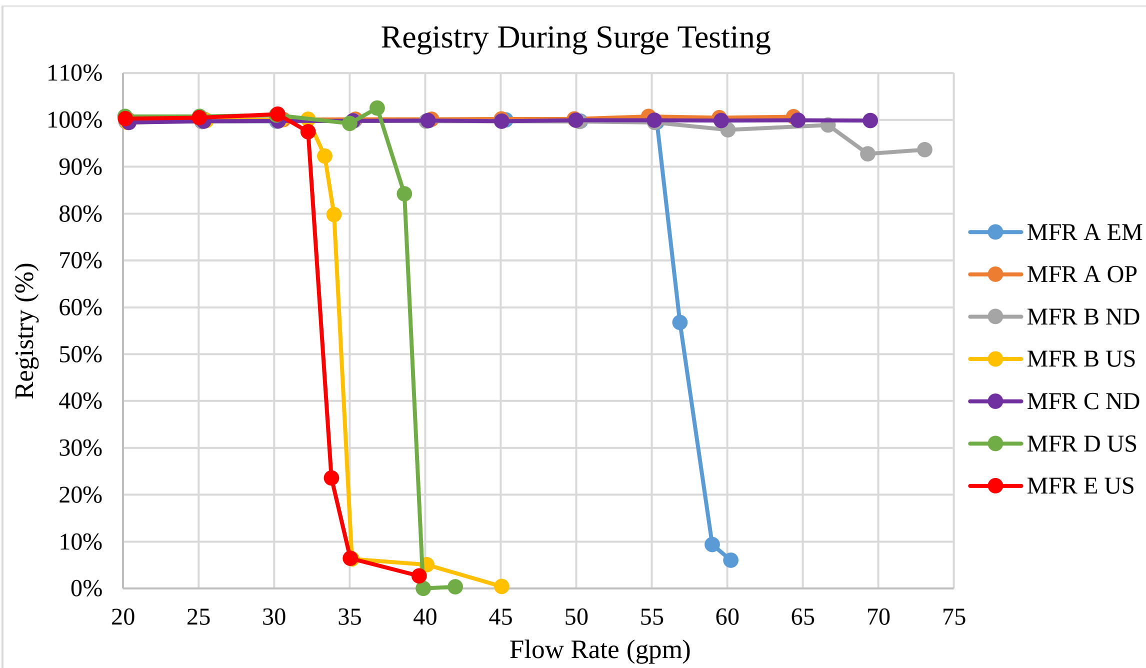

Figure 4. Registry during surge testing

Meter accuracy after surge testing is shown in Figure 5. The flow rates in this figure are the same flow rates tested before surge flow testing. The electronic meters had very similar results for before and after surge flows. Manufacturer C nutating disk meters experienced a decrease in accuracy at the 0.125 and 0.0625 gpm tests. Manufacturer B nutating disk meters had similar accuracy before and after surge flows. It is interesting to note that all the nutating disk meters would still pass AWWA minimum, intermediate, and maximum flow rate standards after surge flow testing. The oscillating piston meters experienced a significant decrease in accuracy starting at the 0.5 gpm test. It is clear from comparing Figures 3 and 5 that the mechanical meters were impacted by surge flows at the lowest flow rates.

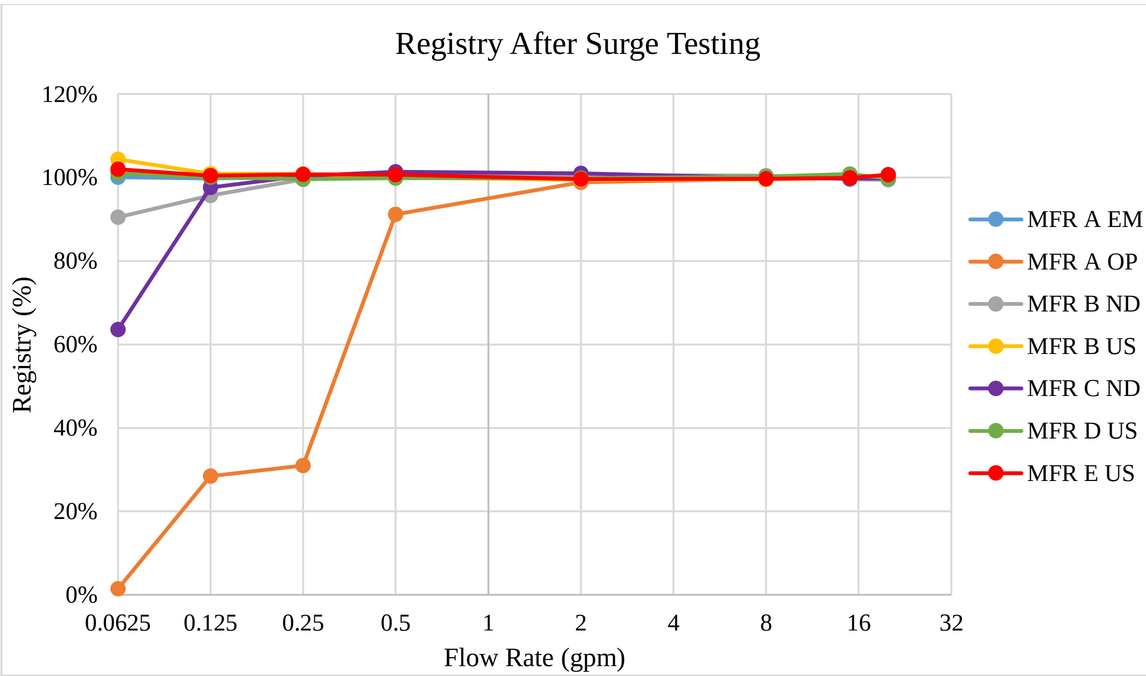

Figure 5. Registry after surge testing

Plots showing meter accuracy from before and after surge testing are included in the Appendix for a clearer comparison of the effects surge flows had on the accuracy of an individual meter type. Again, each of the data points for these figures in the Appendix represent the average of the set of three meters tested.

Pressure Loss Data

All data in this section is presented as net pressure loss. The net pressure loss was determined by subtracting the pressure loss of the test setup with no meter installed from the gross pressure loss measured during the test. Each point on the plots is an individual data point. All pressure loss data is fitted with a second-order polynomial. The data fits the second-order polynomial well, which is expected because of the energy equation.

The net pressure loss for manufacturer A oscillating piston meters are shown in Figure 6. The plot only includes the pressure loss in the normal operating range. On the horizontal axis is flow rate in gpm. The vertical axis is net pressure loss in pounds per square inch (psi). The manufacturer pressure loss data is also included on the plot as a red line.

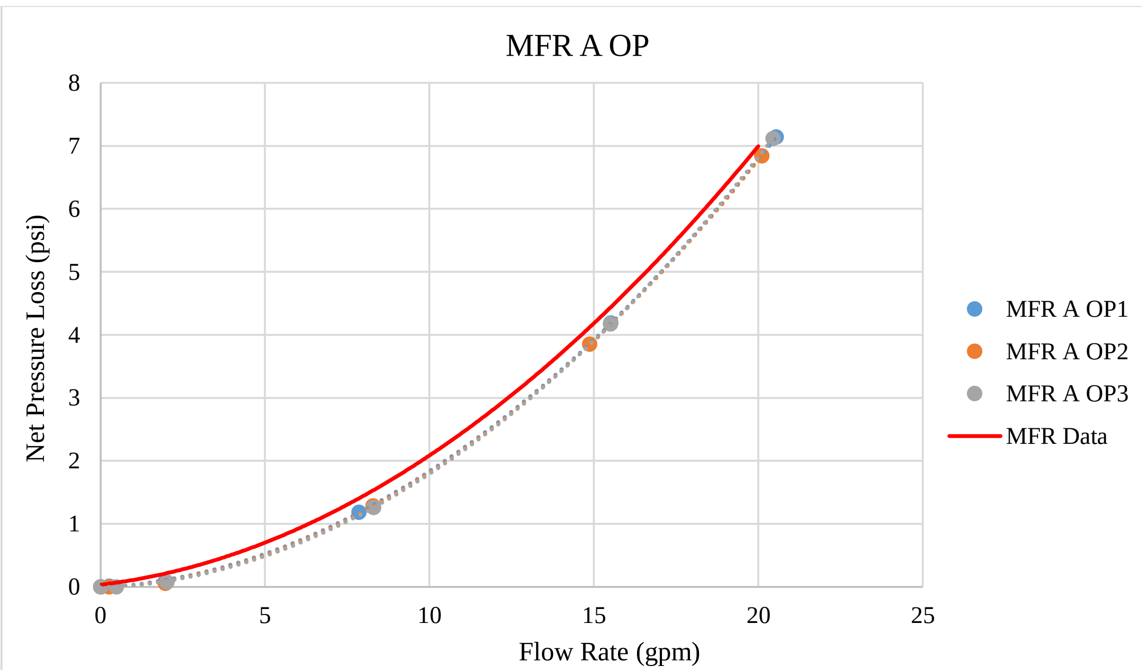

Figure 6. Manufacturer A OP net pressure loss normal operating range

Most meter manufacturers’ pressure loss data is close to the laboratory data. However, some meters have pressure loss curves higher than the manufacturer data. An example of this is shown in Figure 7. Net pressure loss plots for the normal operating range are shown for every meter in the Appendix.

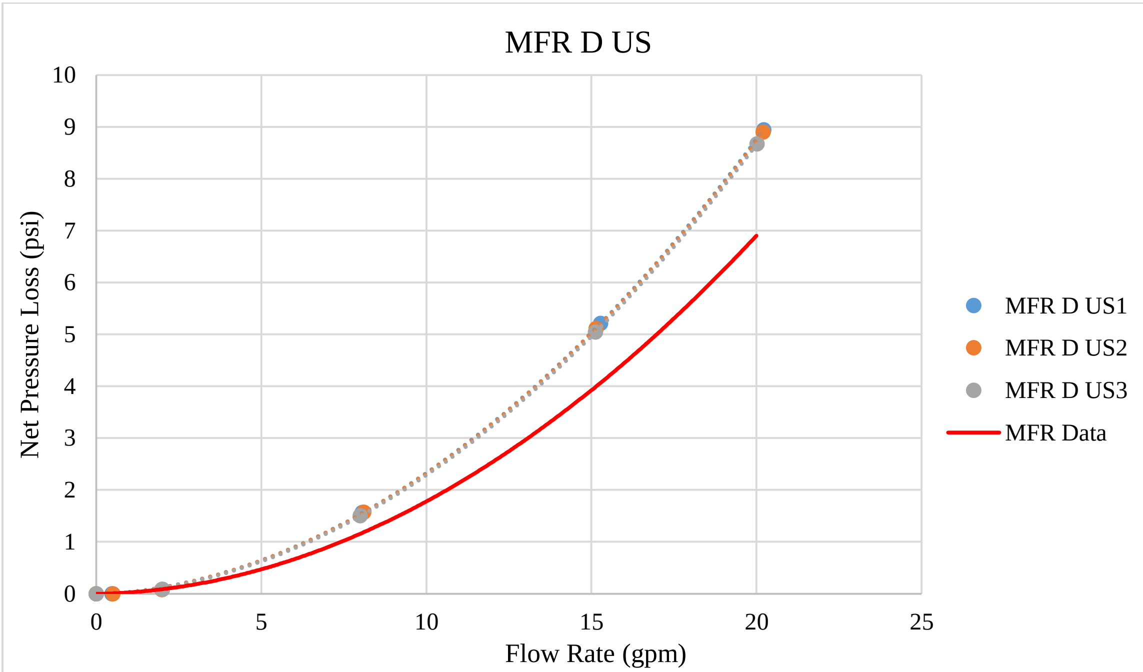

Figure 7. Manufacturer D US net pressure loss normal operating range

The pressure loss in the normal operating range for every meter is shown in Figure 8. Every data point is on this plot. A second-order trend line is fit through each set of three meters. Flow rate in gpm is on the horizontal axis, and net pressure loss in psi is on the vertical axis. For the meters in this study, the order of most pressure loss to least pressure loss created is ultrasonic, oscillating piston, nutating disk, and electromagnetic. The data for each set of meters closely fits a second order polynomial. This indicates that for a given meter type, manufacturer, and size, the pressure loss is repeatable.

The pressure loss during surge flows for every meter is shown in Figure 9. Again, every data point from each meter is shown on this plot. From inspecting the plot, pressure loss varies more within a given meter type at the higher flow rates. This is also clear from comparing Figure 10 with Figure 6. For a given meter type, manufacturer, and size, the pressure loss has more variation with high flow rates than with low flow rates. Plots of every meter during surge flow testing are included in the Appendix.

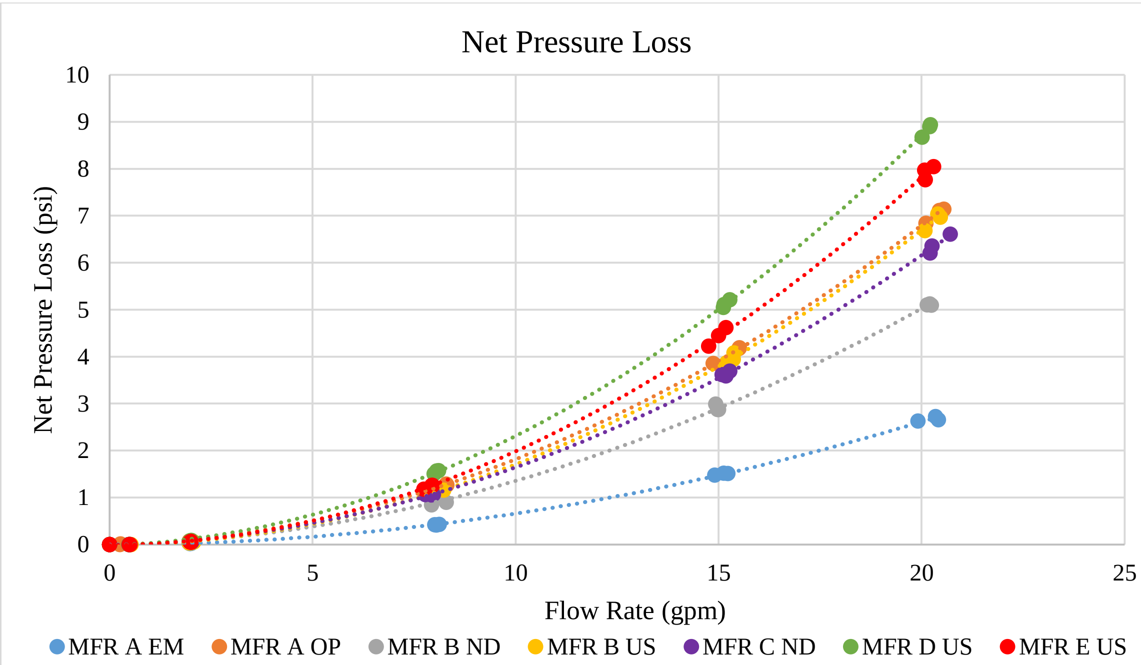

Figure 8. Net pressure loss in the normal operating range

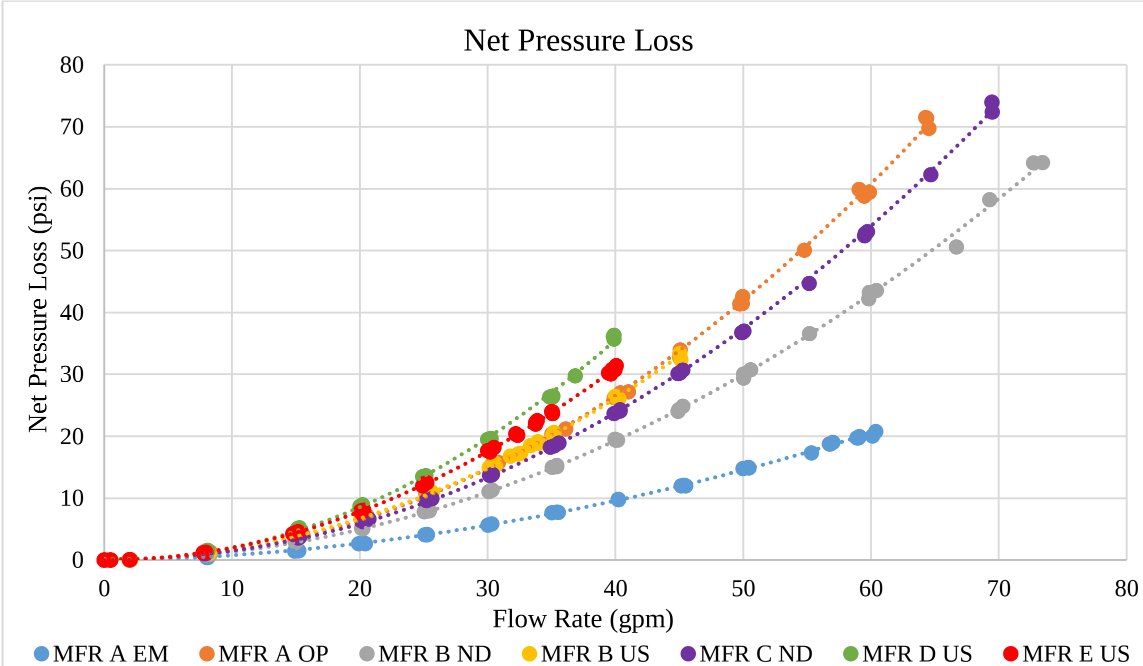

Figure 9. Net pressure loss during surge testing

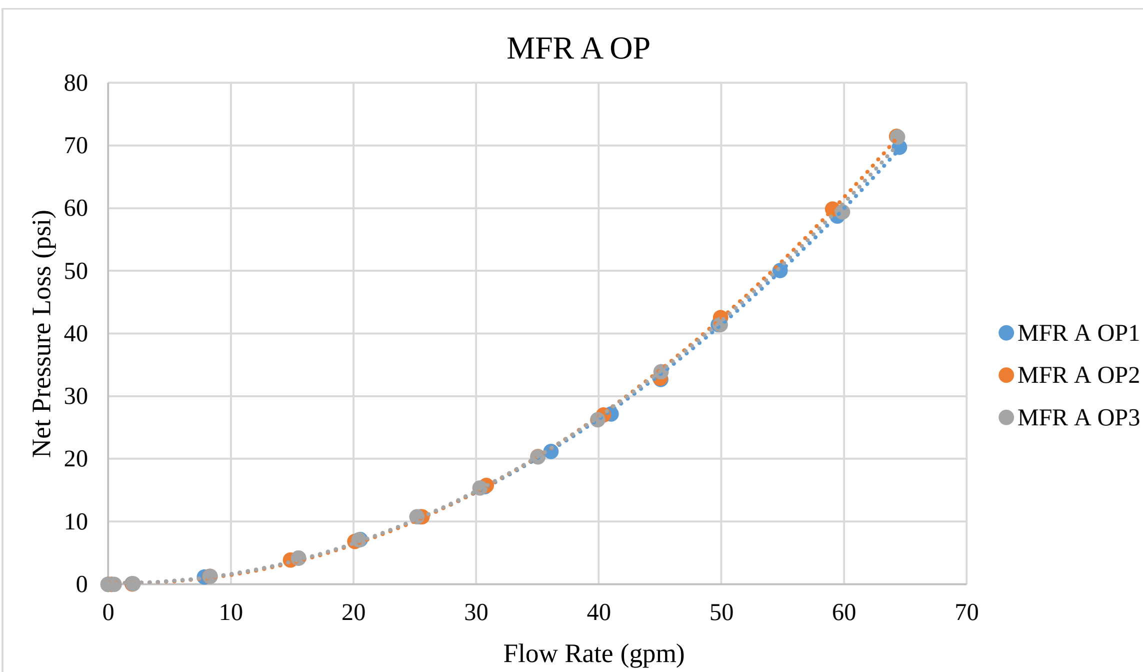

Figure 10. Manufacturer A OP net pressure loss during surge flows

CHAPTER V

CONCLUSIONS

Twenty-one 5/8” x 3/4” residential meters from five manufacturers were tested in this study. The twenty-one meters consisted of seven sets of three meters. Each set of three meters were the same manufacturer, type, and size. The results of this research indicate that some meters tested in this study can exceed maximum operating flow rates without damage.

The ultrasonic meters tested in this study produced more pressure loss than any other meter types tested. Test results showed that the ultrasonic meters significantly decreased in accuracy when surge flow rates exceeded 35 gpm. This may be due to the strength of the sound wave the ultrasonic meters use for flow measurement. The signal strength may not be sufficient to reach the opposite transducer while traveling against the flow, resulting in no flow measurement. However, these meters were just as accurate after surge testing as they were before surge testing.

The electromagnetic meters tested produced the least amount of pressure loss out of all the meters tested. They were accurate up to 55 gpm. The electromagnetic meters had similar accuracy before and after surge flows.

The oscillating piston meters produced the most pressure loss of all the mechanical meters but not more than the ultrasonic meters. The oscillating piston meters were accurate for all surge flows tested. The meters showed a decrease in accuracy after experiencing surge flows. The decrease was apparent below the two gpm test. The decrease in accuracy may be due to internal damage or excessive wear of meter parts.

The nutating disk meters produced less pressure loss than the ultrasonic or oscillating piston meters, but more than the electromagnetic meters. The nutating disk meters were accurate for all surge flows tested. Manufacturer C nutating disk had diminished accuracy after surge tests for flows below 0.25 gpm. This may be due to internal damage or excessive wear of meter components. Manufacturer B nutating disk had similar accuracy before and after surge flows.

This research indicates that displacement meters were generally affected by surge flows. This was apparent due to a decrease in accuracy at low flow rates after surge flows occurred. However, the mechanical meters did not have an increase in pressure loss due to any mechanical failure as a result of surge testing. No meters mechanically failed due to internal parts breaking. It is unclear whether the mechanical meters in this study had a decrease in accuracy due to damage or wear of internal parts. Future work taking apart meters that have a decrease in accuracy due to surge flows may provide insights to whether the meter experiences excessive wear or actual damage of internal parts.

The electronic meters all returned to normal operation after experiencing surge flows. This suggests that they may not be impacted significantly by surge flows. However, meter accuracy during very high surge flows was not optimal. Excessive pressure loss with the ultrasonic meters could also be a concern if used in surge flow scenarios.

The results of this study are intended to be used when choosing a residential water meter for a connection. For utilities, the results from this study indicate that some meter types may be advantageous to use at connections where flows above a meter’s rated capacity are possible. Being able to use a smaller meter at a connection would improve water measurement at low flow rates. If using a smaller meter at a connection, it would be necessary to ensure the pressure loss at the surge flows do not impact the operation of the connection demands.

Limitations

Several limitations exist within the results of this research. Only new meters were tested. Meters that have significant throughput may respond differently to surge flows than the meters in this study.

Relatively short surge flow durations were tested in this study. Test times for surge flows only ranged from 2.5 to 4 minutes. Situations that would cause a surge flow may be much longer than the durations tested. The impact of surge flows for extended durations may be different than the findings in this study.

This research did not include a comprehensive set of meters. Other meter types may respond differently. The same meter types from different manufacturers may also perform differently than the meter types tested in this study.

Some meters experienced a decrease in accuracy after surge testing at the lowest flow rates. Unfortunately, it is unclear at what point the meters became compromised due to surge flows. As noted in the test setup and procedure, the two gpm test was used as a check during and after surge testing to determine if a meter had been compromised. This was not a good indicator for determining if a meter had been compromised because all meters always performed within specification at this flow rate. Using a lower flow rate as a metric for meter integrity may have helped determine the exact point where certain meters were impacted by surge flows.

REFERENCES

Ahrens, Marty, 2017. *U.S. Experience with Sprinklers*. National Fire Protection Association. https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics/Fire-Protection-Systems/ossprinklers.pdf

AWWA, 2012 (5th ed.). Manual of Water Supply Practices, M6. *Water Meters—Selection, Installation, Testing, and Maintenance.* AWWA, Denver.

AWWA, 2014 (3rd ed.). Manual of Water Supply Practices, M22. *Sizing Water Service Lines and Meters.* AWWA, Denver.

NFPA, 2016. National Fire Protection Association. *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes.*

NFPA, 2018. National Fire Protection Association. *Fire Sprinkler Initiative: Bringing Safety Home*. https://www.nfpa.org/Public-Education/Campaigns/Fire-Sprinkler-Initiative/Legislation-and-adoptions/Sprinkler-requirements

Sumrak, McKenna L.; Johnson, Michael C.; & Barfuss, Steven L., 2016. *Analysis of Meter Registry Uncertainty*. http://dx.doi.org/10.5942/jawwa.2016.108.0138

Utiskul, Yunyong and Wu, Neil P., 2016. *Residential Fire Sprinklers—Water Usage and Water Meter Performance Study.* The Fire Protection Research Foundation, Quincy, Massachusetts.
http://osfm.fire.ca.gov/pdf/firemarshal/RFWaterUsageWaterMeterPerformance.pdf

APPENDIX

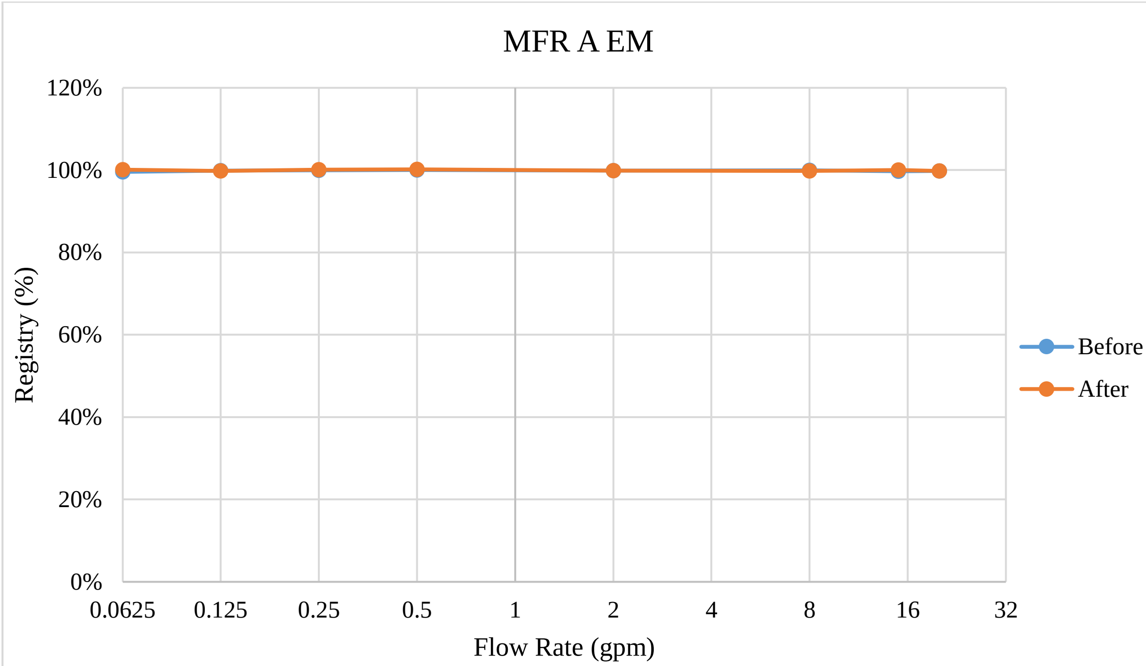

Figure 11. Manufacturer A EM registry normal operating range

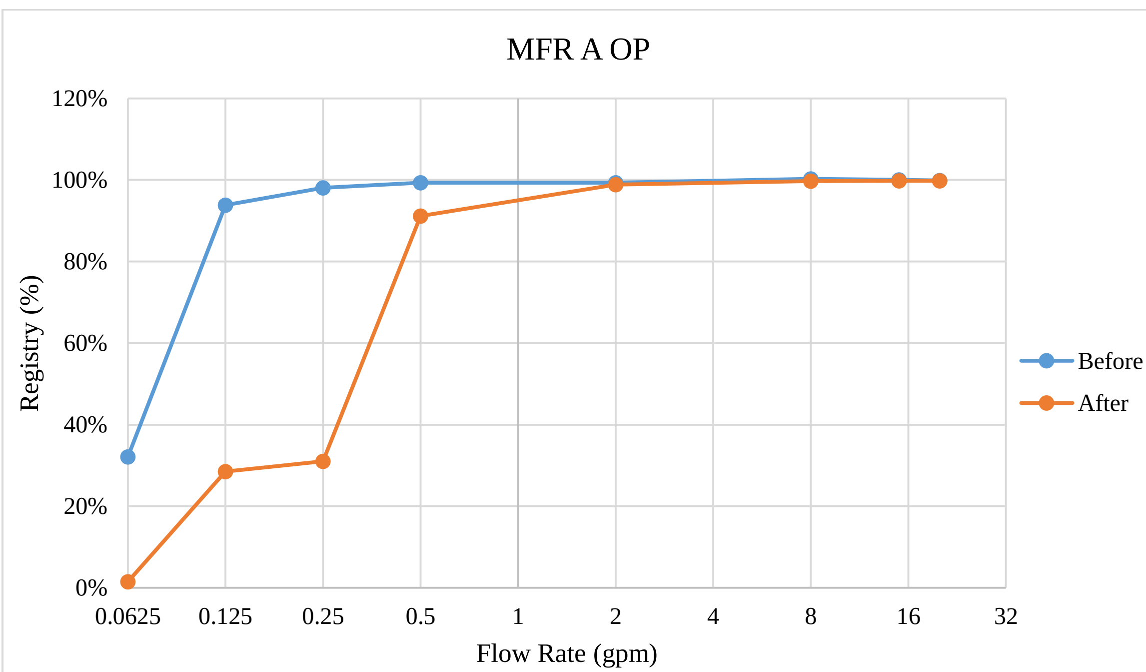

Figure 12. Manufacturer A OP registry normal operating range

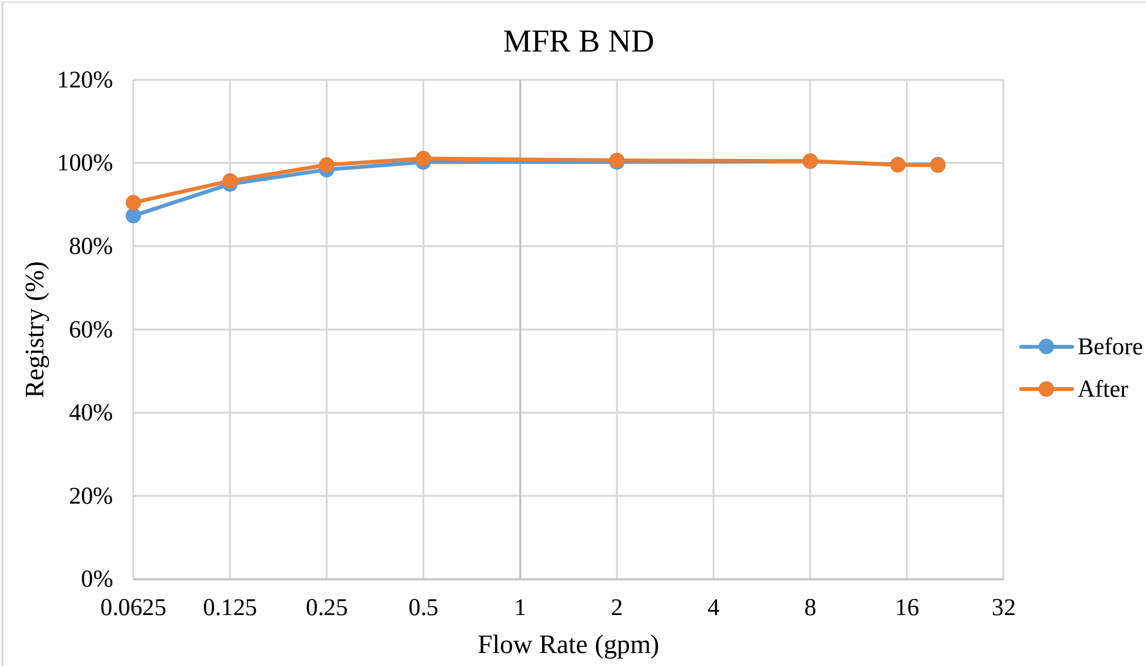

Figure 13. Manufacturer B ND regsitry normal operating range

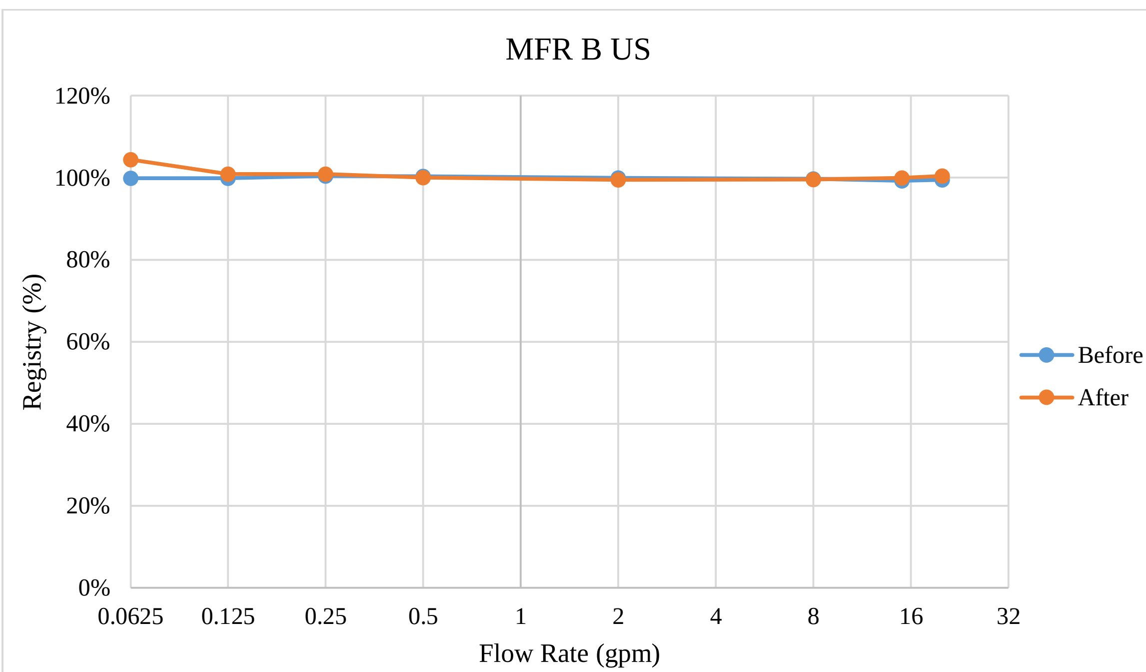

Figure 14. Manufacturer B US registry normal operating range

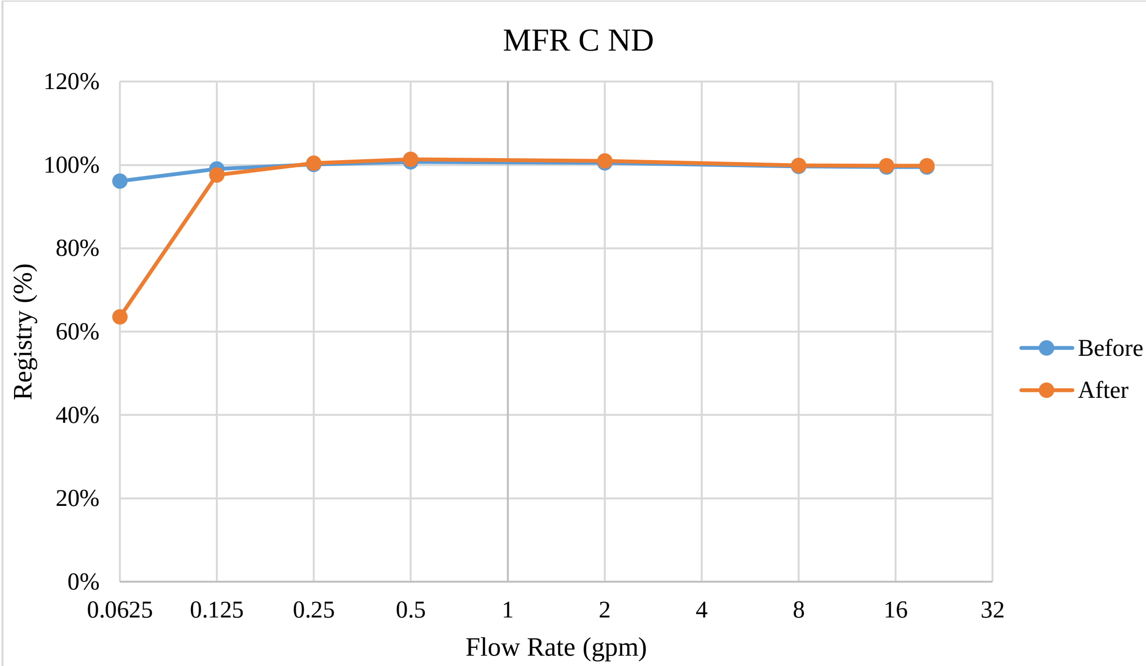

Figure 15. Manufacturer C ND registry normal operating range

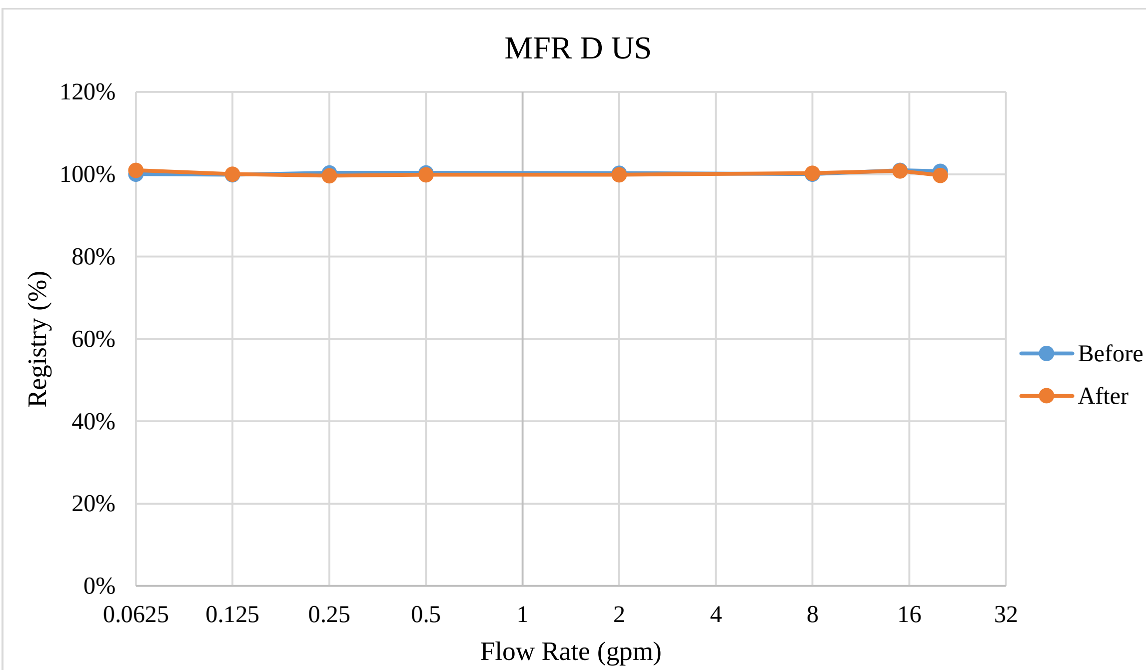

Figure 16. Manufacturer D US registry normal operating range

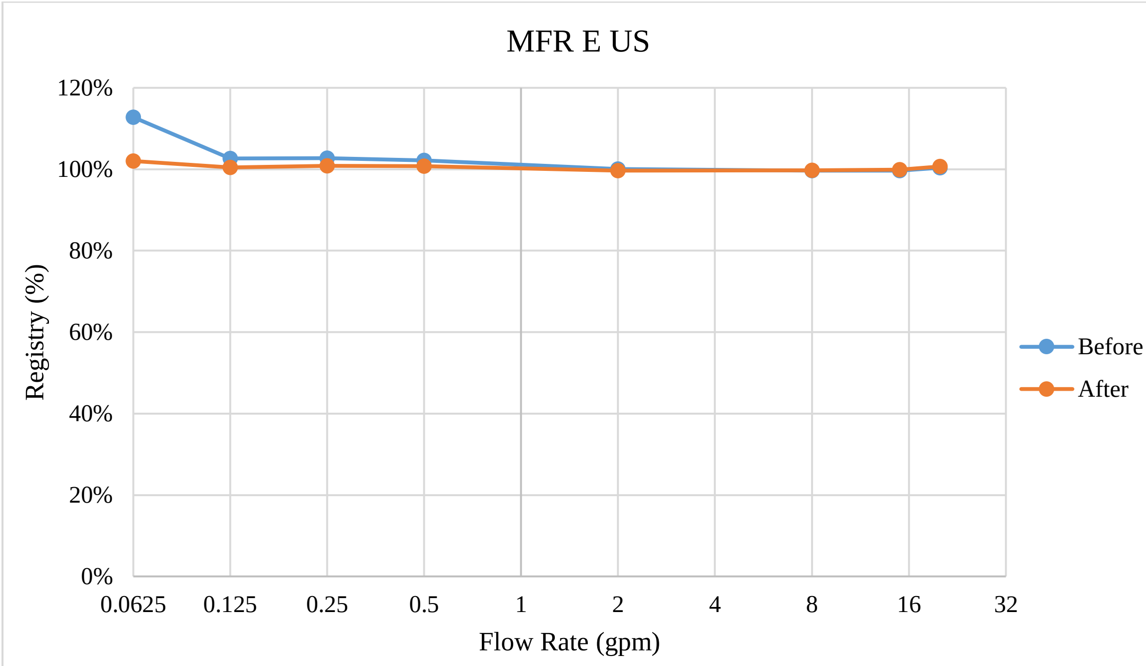

Figure 17. Manufacturer E US registry normal operating range

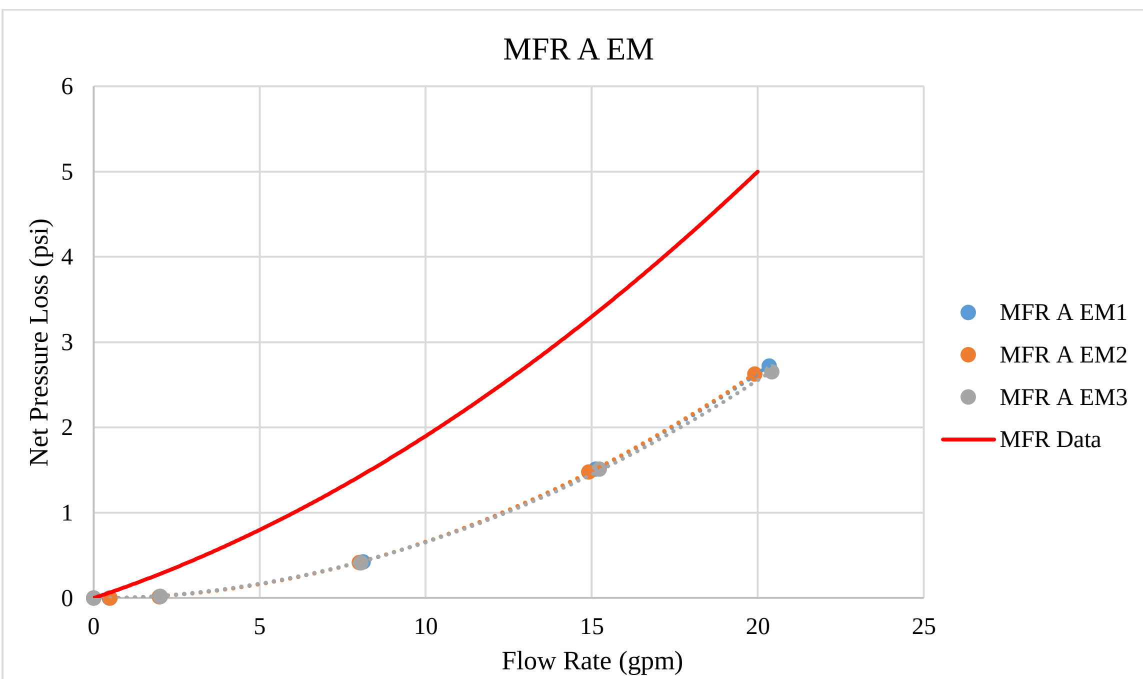

Figure 18. Manufacturer A EM net pressure loss normal operating range

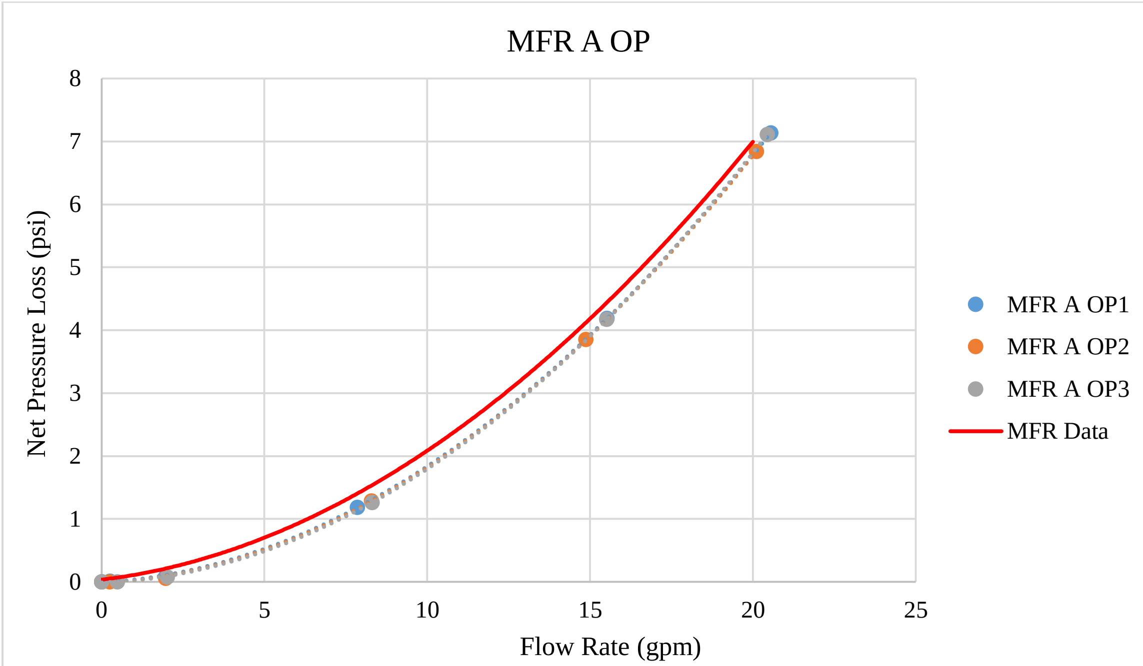

Figure 19. Manufacturer A OP net pressure loss normal operating range

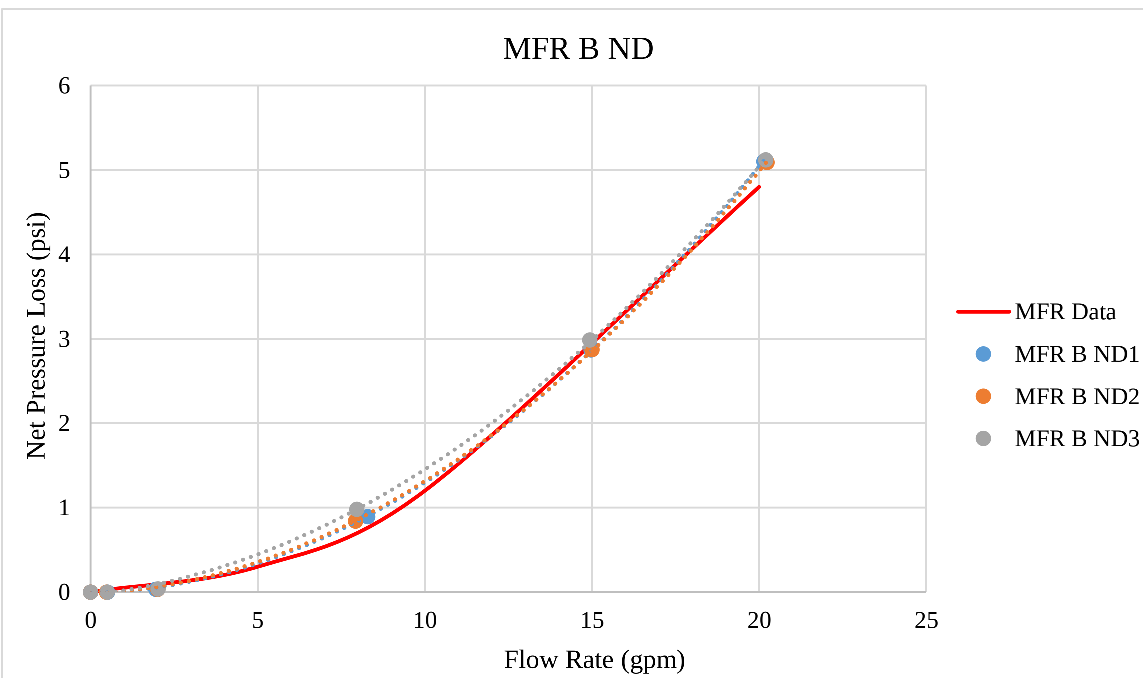

Figure 20. Manufacturer B ND net pressure loss normal operating range

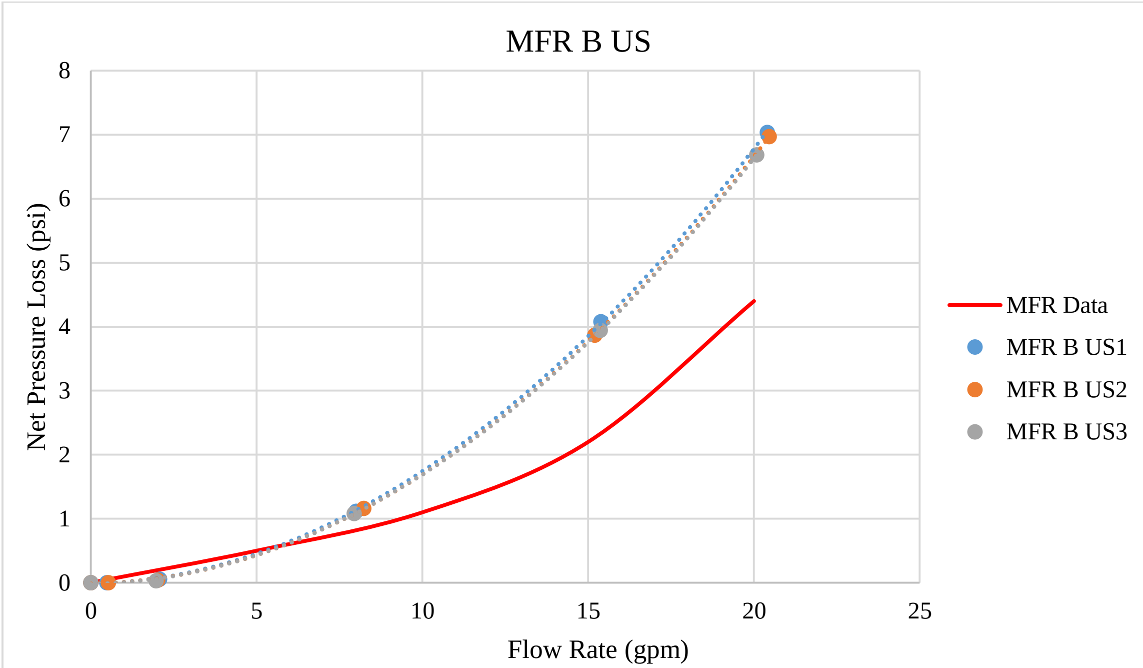

Figure 21. Manufacturer B US net pressure loss normal operating range

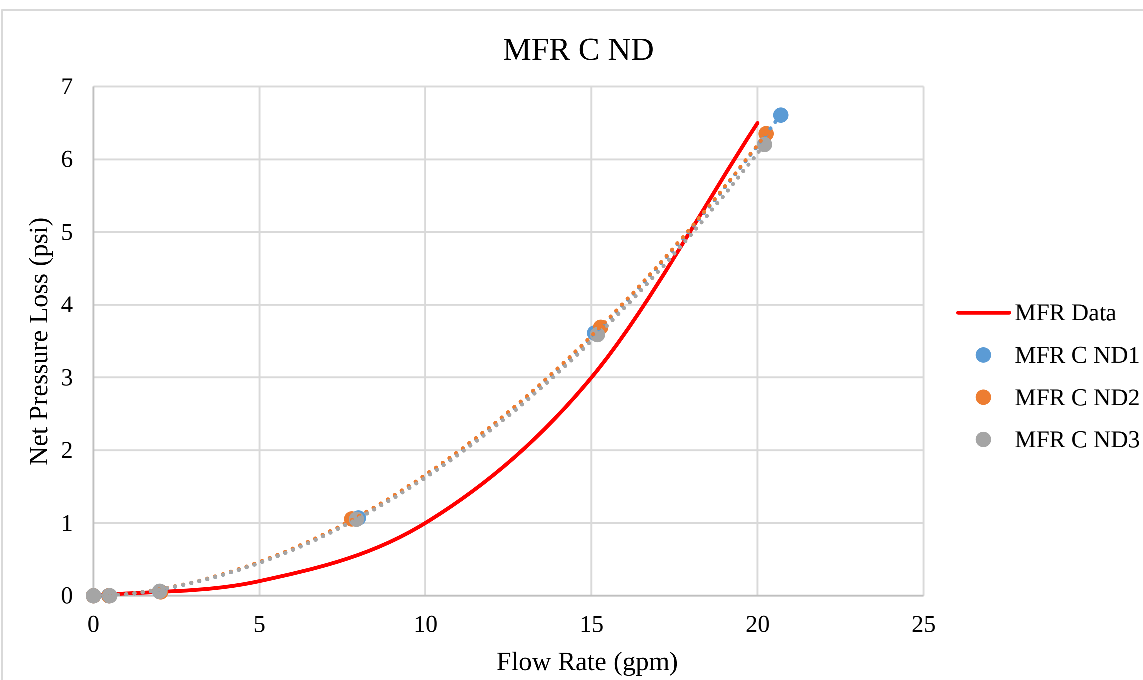

Figure 22. Manufacturer C ND net pressure loss normal operating range

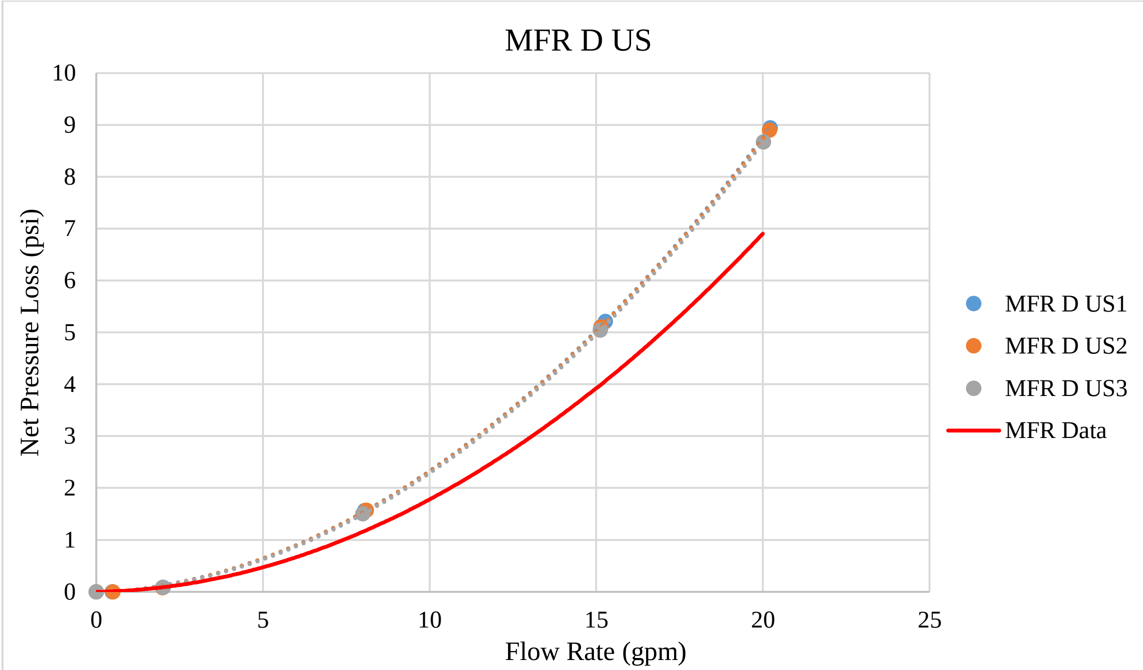

Figure 23. Manufacturer D US net pressure loss normal operating range

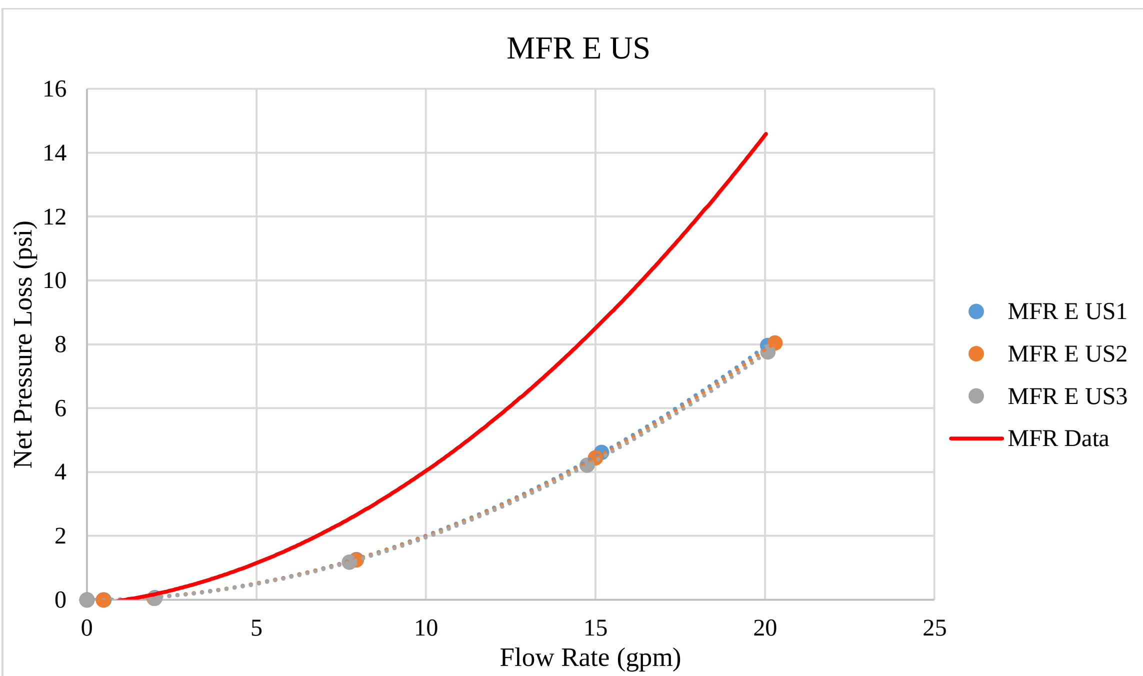

Figure 24. Manufacturer E US net pressure loss normal operating range

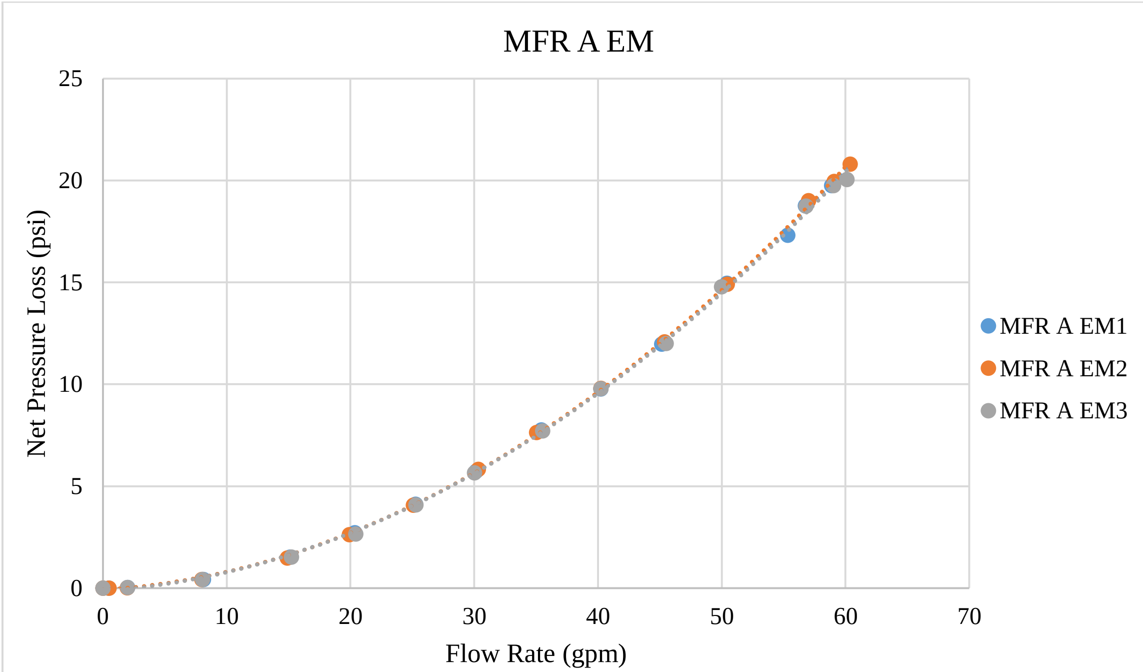

Figure 25. Manufacturer A EM net pressure loss during surge flows

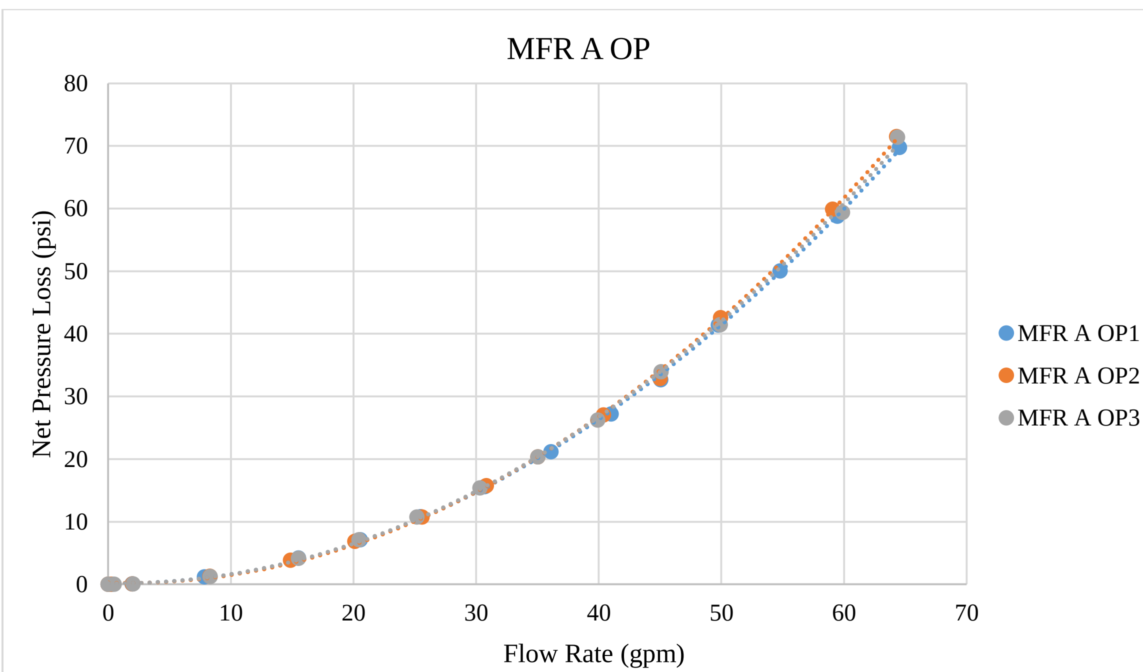

Figure 26. Manufacturer A OP net pressure loss during surge flows

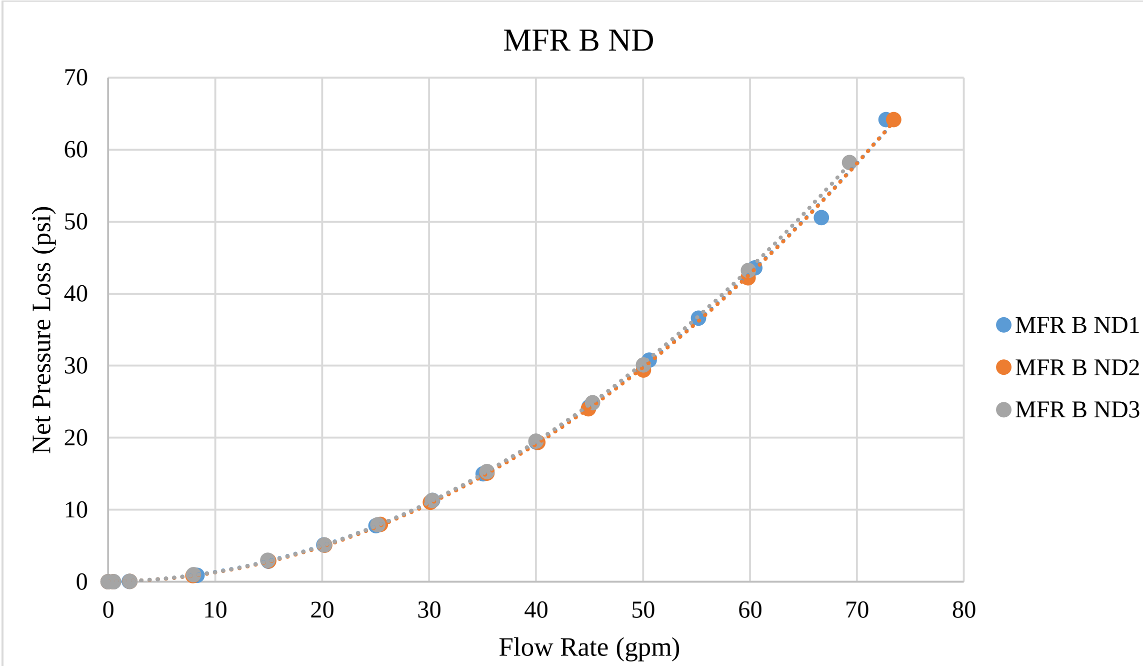

Figure 27. Manufacturer B ND net pressure loss during surge flows

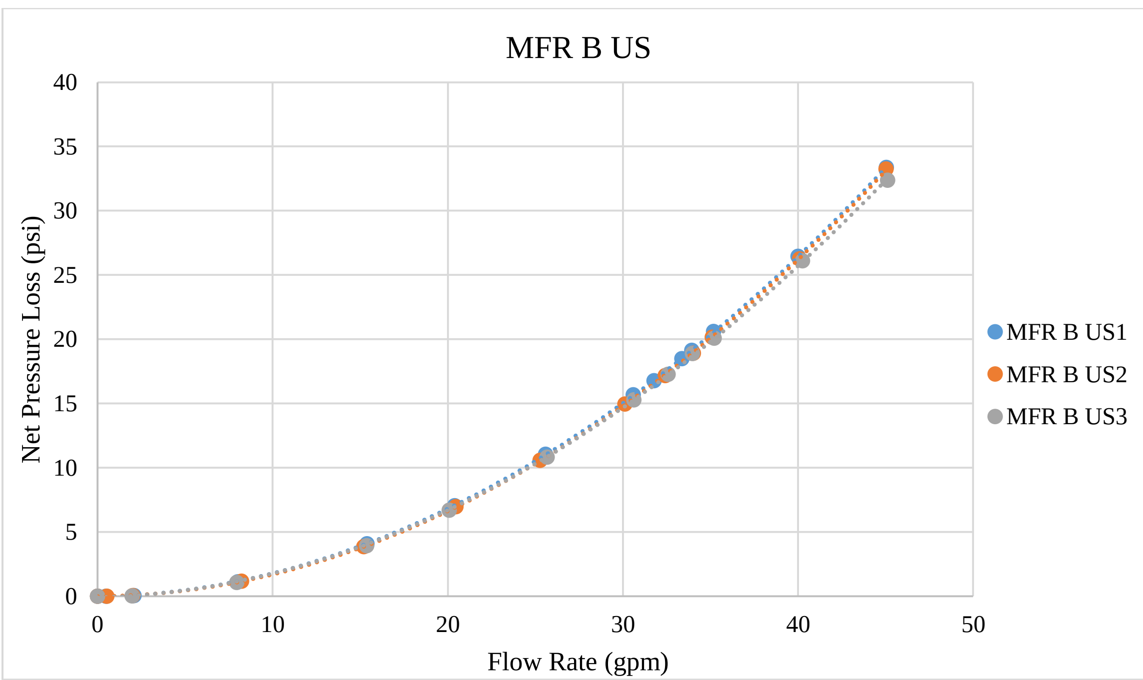

Figure 28. Manufacturer B US net pressure loss during surge flows

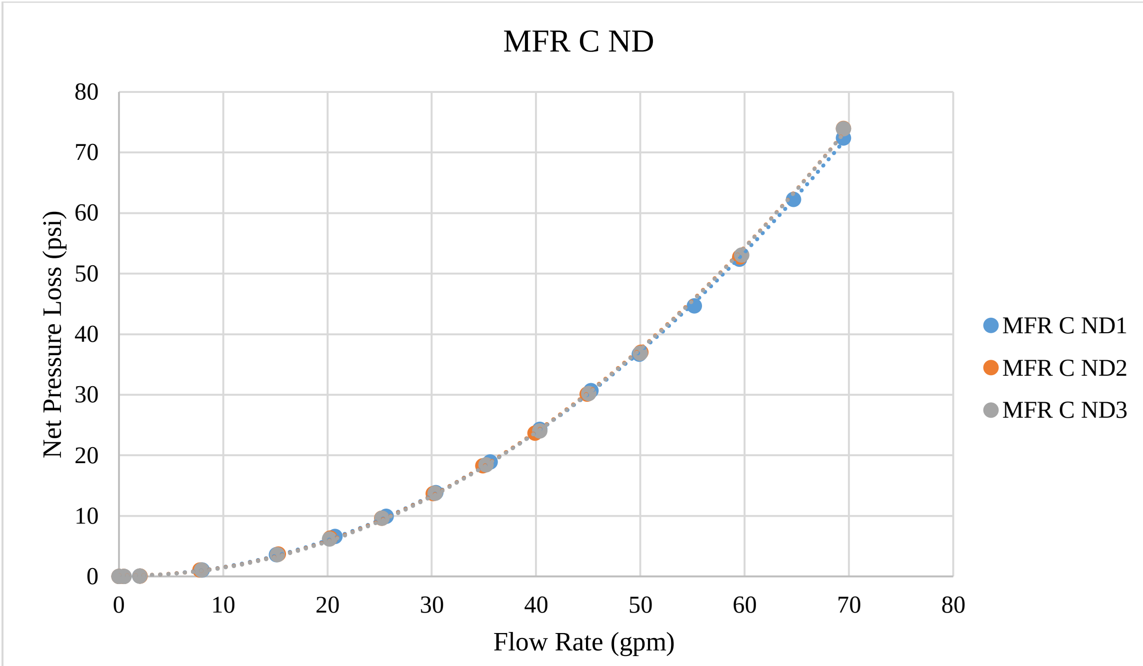

Figure 29. Manufacturer C ND net pressure loss during surge flows

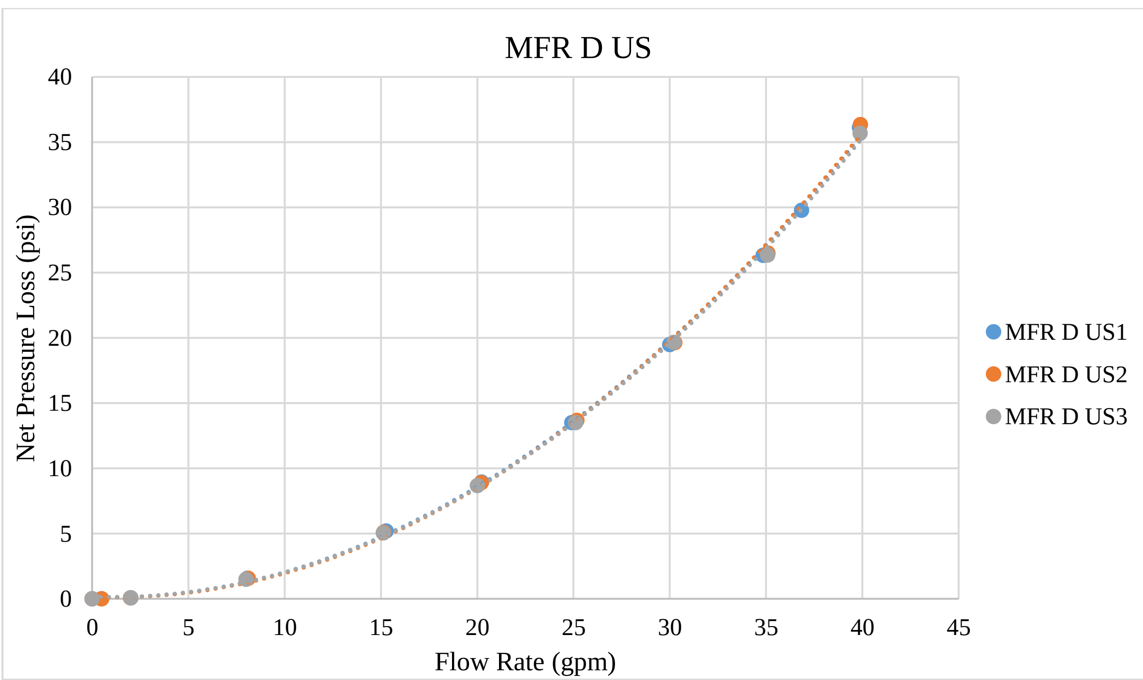

Figure 30. Manufacturer D US net pressure loss during surge flows

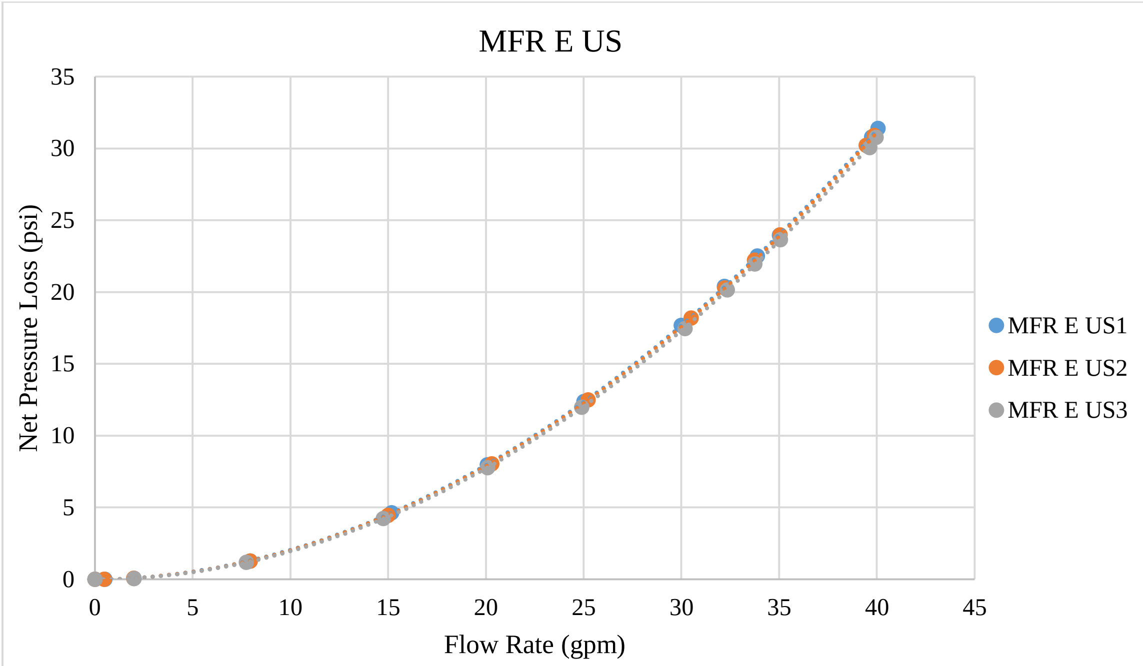

Figure 31. Manufacturer E US net pressure loss during surge flows